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CRITIQUE FOR THE CENTRIFUGE AS A STRESSING DEVICE

Charles Libove

Syracuse University

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The results of this study provide mathematical relationships to theoretically assess the capabilities of the centrifuge test as a stressing device for the following microelectronic components: wires and wire bonds, chip and substrate attachment, lids and bases of rectangular flat-packs. The results of the study suggest that the centrifuge is of marginal utility as a stressing device for the above-mentioned components.

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CONTENTS

EVALUATION

The constant acceleration test of MIL-STD-883, "Test Methods and Procedures for Microelectronics," requires the non-destructive centrifuge testing of microelectronic devices. The prime objective of this effort was to theoretically evaluate the capabilities of the centrifuge to mechanically stress the wires and wire bonds, chip and substrate attachments, and the lids and bases of sealed rectangular flat-packs. The significant results of this evaluation are as follows:

(a) The centrifuge is of marginal utility for the stressing of wires and wire bonds, because of the low mass of these components and possible strength limitations of the package.

(b) For the same reasons, the centrifuge is of marginal utility for stressing normal chip-to-substrate and chip-to-package attachments.

(c) The centrifuge might be capable of producing significant bond stresses in chips which are bonded to a few pedestals or bumps, as in face-down bonding.

(d) The centrifuge might also be capable of producing significant stresses in substrate-to-package bonds.

(e) The centrifuge can produce significant flexural stresses in lids and bases of the larger flat-packs, but these effects can be more easily produced by hydrostatic pressure.

The results of this program, if verified experimentally, will provide a good foundation for future revisions of centrifuge test levels and procedures and will also be used in support of the Air Force/NASA task to establish screening requirements for Class S hybrids.

Peter F. Manno

PETER F. MANNO
Project Engineer

I. INTRODUCTION

Constant acceleration in a centrifuge is one of the standard screens to which microelectronic devices may be subjected for the purpose of aggravating and detecting mechanical weaknesses (Reference 1).

The purpose of the present report is to assess theoretically the capabilities of the centrifuge as a mechanical stressing device for the following types of microelectronic components: wires and wire bonds, chip and substrate attachments, lids and bases of rectangular flat-packs.

The results of the present study suggest that the centrifuge is of marginal utility as a stressing device for the above-mentioned components.

A possibly useful by-product of the present investigation is the stress analysis of a wire in a pull or centrifuge test, taking into account the extensibility of the wire, a factor which has been ignored in previous analyses. The wire extensibility usually has a negligible effect, but it can become important for wires with very little or no initial slack, in which case its neglect leads to an over-estimate of the wire tension and bond forces.

Acknowledgment.- This study was performed under Contract No. F30602-75-C-0121 with the Rome Air Development Center at the suggestion of Peter Manno, John Farrell and Edward O'Connell of that Center. Their helpful discussions with the author are greatly appreciated. The author is also indebted to Mr. Richard Gordon, Sales Manager of Consolidated Refining Company, Inc., for providing useful information on the tensile properties of gold and aluminum wires.

II. WIRES AND WIRE BONDS

A. Nomenclature and Physical Constants.- We consider a wire (Figure 1) that spans a horizontal distance S and, in its unstressed state, has a length of L_o and a cross-sectional area of A. Its Young's modulus and unstressed specific weight will be denoted by E and γ, respectively, and the assumed values of these constants for two common wire materials are tabulated below (Table 1).

Table 1.- Properties of Gold and Aluminum

	Gold	Aluminum
E (psi)	12×10^6	10×10^6
γ (lb/in.^{3})	.7	.1

A parameter that will be needed later is the "excess-length parameter" R, defined as follows:

$$R = \frac{L_o - S}{S} \qquad \text{or} \qquad \frac{L_o}{S} = 1 + R \tag{1}$$

In principle, R can be determined by measuring L_o and S and substituting their values in Eq. (1). However, L_o may be rather difficult to measure. Much easier to estimate is the loop height H when the unstressed wire is in the curved (assumed to be catenary) shape of Figure 1(a) or is gently pulled into the bilinear shape of Figure 1(b) (the two values of H for a given wire will of course be different). Therefore, graphs are provided in Figure 2 from which R can be determined if the dimensionless loop-height parameter H/S is known for either of these two shapes. The curves in Figure 2 can be accurately approximated by the following equations if H/S is less than 0.2:

$$R = \frac{8}{3}(H/S)^2 \quad \text{(lower curve)} \tag{2}$$

$$R = 2(H/S)^2 \quad \text{(upper curve)} \tag{3}$$

It will be noted that R is usually of a much smaller order of magnitude than H/S.

Under its distributed inertia loading in a centrifuge or its concentrated loading in a pull test, the wire will develop a stressed length of L and will exert forces of magnitude T_o on its bonds (Figure 3). The corresponding maximum nominal tension stress in the wire will be

$$\sigma = T_o/A \tag{4}$$

occurring at the ends.

The magnitude of the inertia loading in a centrifuge test will be characterized by the parameter G, defined as the number of g's (g = acceleration of gravity) of centripetal acceleration that the wire is experiencing. The intensity of the loading in a pull test will be described by the magnitude P of the pulling force shown in Figure 3(b). Both loads are assumed to be so oriented as to maintain the wire in a symmetrical shape.

B. Wire Stress in a Centrifuge Test.- The stress analysis of a wire in a centrifuge test, taking extensibility into account on the basis of Hooke's Law, is carried out in Appendix A. The results are summarized in Figure 4, where the dimensionless wire-stress parameter T_o/AE is plotted as a function of the dimensionless inertia-loading parameter $G\gamma S/E$ for different values of the excess-length parameter R. For any given test one would know the value of the abscissa. For that abscissa the ordinate value of T_o/AE would be read from the appropriate R curve. Multiplication of the T_o/AE value by the known value of AE or E would give the bond force T_o or the maximum wire stress T_o/A.

To facilitate the use of Figure 4, two "bench-mark" values of the abscissa, corresponding to certain test conditions, are indicated by arrows. Since the abscissa is directly proportional to G and S, it is easy to compute its value in <u>any</u> test of a gold or aluminum wire by multiplying one of the bench-mark values by appropriate ratios.

A bench-mark ordinate is also marked on Figure 4 which indicates that $T_o/AE = .001$ corresponds to a maximum tensile stress of 10,000 psi in aluminum wire and 12,000 psi in gold wire. The gold and aluminum wire stresses associated with any other T_o/AE value, say $(T_o/AE)_1$, can be found by multiplying the above stresses by the ratio of $(T_o/AE)_1$ to .001.

In order to judge whether or not a certain wire stress, $\sigma = T_o/A$, is significant, one could compare it with the ultimate tensile strength σ_u of the material. This varies greatly with the manufacturer and the temper of the wire. Typical values are given in Table 2 below for small diameter wires (1.5 mils and less). Manufacturers' guaranteed values may be lower than the ones in the table.

Table 2.- Typical Values of σ_u (psi) for Wire

	Gold	Aluminum
Annealed Temper	25,000	37,000
Hard Temper	60,000	60,000

Whether or not wire extensibility has a significant effect on the stresses can be judged from the slopes of the curves in Figure 4. A slope that is 45° or nearly so indicates that wire extensibility has a negligible effect. Where the curves have such a slope, T_o/AE is proportional to $G\gamma S/E$; then T_o and T_o/A are actually independent of E. Where the slope is significantly different from 45°, wire extensibility has a significant effect; this happens for the smaller values of R when $G\gamma S/E$ is sufficiently high.

Figure 4 is based on the assumption that the wire material obeys Hooke's law. Therefore, strictly speaking, any data obtained from that figure are valid only if the maximum stress, $\sigma = T_o/A$, is below the proportional-limit stress σ_p associated with the point P of the stress-strain curve where stress stops being proportional to strain (see Figure 5). If the stress $\sigma = T_o/A$ falls above point P, say at Q, the curves of Figure 4 will still be approximately correct provided that E in the ordinate and abscissa labels is changed to E_s, where E_s is the secant modulus associated with the stress $\sigma = T_o/A$ (see Figure 5). The approximation becomes better as H/S becomes smaller, for then the stress is more nearly constant at the value σ along the entire length of the wire. Since E_s is itself a function of σ, it is clear that trial-and error calculation will be required to determine σ when $\sigma > \sigma_p$.

For hard-tempered wires it may be permissible to idealize the actual (curving) stress-strain curve to a bilinear form, as in Figure 6. Then Figure 4 would be valid without modification for all σ's up to σ_u.

C. Wire Stress in a Pull Test.- The pull test of Figure 3(b) is analyzed in Appendix B and the results are given in Figure 7 by graphs that are similar to those in Figure 4. The dimensionless loading parameter in this case is P/AE, and three "bench-mark" values of this parameter are indicated, corresponding to minimum pre-seal pull strengths specified for test condition D in Table 1 of Method 2011.1 of Reference 1.

As indicated in Figure 7, R = .155 represents a dividing line. For wires with less excess length (which is the usual case) the bond force T_o will be greater than the pull force P, while for wires with more excess length the opposite will be true.

As in the case of Figure 4, the more the slope of a curve deviates from 45°, the more significant is the effect of wire extensibility. Also as in Figure 4, the curves of Figure 7 can be used for $\sigma = T_o/A > \sigma_p$ provided that the Young's modulus E is replaced by the secant modulus E_s associated with the stress σ. In fact, this procedure is more accurate in the present case, because the wire stress is constant along the entire length of the wire in the pull test, whereas it is only approximately so in the centrifuge test.

D. Comparison of Centrifuge and Pull Test.- A comparison of Figures 4 and 7 shows that the centrifuge is generally much less effective than the pull test in stressing wires and wire bonds. For example, let us consider the four bench-mark pull tests of Figure 7, which, as already noted, represent minimum required pre-seal pull strengths specified in MIL-STD-883A. Supposing R to be .03, which is a reasonable value, we find that all of those pull tests produce tensile stresses exceeding 10,000 psi in aluminum wires or 12,000 psi in gold wires ($T_o/AE = .001$). On the other hand, for the same R the three bench-mark centrifuge tests of Figure 4 produce T_o/AE values of .0001 and .00026, implying wire stresses that are at most 10% and 26% of those produced by the pull tests.

In order to achieve a stress of 10,000 psi in an aluminum wire with $R = .03$ at 40,000 g's, Figure 4 shows that the span would have to be one inch. To achieve 12,000 psi at 30,000 g's in a gold wire the span would have to be four-tenths of an inch. Since such large spans are unlikely to occur in practice in microelectronic devices, and since centrifuge accelerations exceeding 30,000 or 40,000 g's are difficult to achieve and may be destructive of other package components, it appears that the centrifuge will

generally be incapable of producing wire stresses comparable to those produced in the MIL-STD-883A pull tests. A similar conclusion was reached by other investigators (see, for example, Reference 2).

A more thorough comparison of the centrifuge and pull tests can be made by comparing the $G\gamma S/E$ value from Figure 4 and the P/AE value from Figure 7 for many selected combinations of R and T_o/AE. Each such comparison will give us a pair of tests (one centrifuge, the other pull) that are equivalent in the sense that they will produce the same stress in a wire with the given value of R. Such comparisons show that the ratio r of the equivalent load parameters, that is,

$$\frac{P/AE}{G\gamma S/E} = \frac{P}{G\gamma SA} \equiv r\ , \tag{5}$$

depends on R but is virtually independent of T_o/AE. The results of the comparisons can therefore be put in the form of a single curve, Figure 8. Using Eq. (5) in the form

$$P = rG\gamma SA \qquad \text{or} \qquad G = P/r\gamma SA \tag{6}$$

and taking r from Figure 8, one can readily find the P of a pull test that will stress any wire and its bonds as severely as a given number (G) of g's in a centrifuge test. Conversely, given the P of a pull test, one can find how many (G) g's of centrifuge acceleration will be equivalent in severity to that pull test.

For wires without excessive loop height, R will usually be smaller than 0.1. Then r may be taken as 0.65 with little error, and the equivalence relation (6) will become

$$P = .65G\gamma SA \qquad \text{or} \qquad G = P/.65\gamma SA \tag{7}$$

To illustrate the use of this result, let us ask what centrifuge acceleration is equivalent to a 3-gram pull on a 1-mil diameter gold wire with a 100-mil span. From the given data we have

$$P = 3(.002205) = .006615 \text{ lb}$$

$$\gamma = .7 \text{ lb/in.}^3$$

$$S = .100 \text{ in.}$$

$$A = \frac{\pi}{4}(.001)^2 = .785 \times 10^{-6} \text{ in.}^2$$

Substitution of this information into the second form of Eq. (7) gives

$$G = \frac{.006615}{.65(.7)(.1)(.785 \times 10^{-6})} = 185{,}000$$

Thus, 185,000 g's of centrifuge acceleration would be required to produce the same wire and bond stresses as the given pull test. This is probably an impractically high value.

III. CHIP AND SUBSTRATE ATTACHMENT

A. Conventional Bonding.- The rectangular parallelepiped in Figure 9, of dimensions a, b and t and specific weight γ, represents a chip bonded to a substrate, or a substrate bonded to a package base. The two vectors represent two possible orientations of a centrifugal force that might tend to cause separation of the object from the thing to which it is attached. In either case the magnitude of the force is

$$G\gamma abt \tag{8}$$

where G is the number of g's of acceleration of the object. The corresponding nominal stress in the bond, obtained by dividing (8) by the gross bonding area, ab, is

$$S_{nominal} = G\gamma t \tag{9}$$

and this is either a tensile or a shear stress, depending on the orientation of the package in the centrifuge. If there is a "voids ratio" V in the bond, the net bond area will be $(1 - V)ab$, and the actual mean stress in the bond will be

$$S_{actual} = \frac{G\gamma t}{1-V} \tag{10}$$

On the basis of Eq. (10) we can investigate the likelihood of the centrifuge producing separation of a poorly bonded chip or substrate. For this purpose let us set G at 50,000, which is Reference 2's estimate of the largest number of g's one can conveniently and safely use, and set γ at .140 lb/in.^{3} (3.89 grams/cc), which corresponds to one of the denser substrate ceramics. With this input, Eq. (10) gives the stress versus

thickness relationship shown in Figure 10. Figure 10 can be used for other values of G and γ by simply multiplying the ordinate values by

$$\frac{G}{50,000} \cdot \frac{\gamma}{3.89} \tag{11}$$

where γ is the specific gravity (i.e., the density in grams/cc). Thus, for silicon chips ($\gamma = 2.4$) tested at 50,000 g's, one should multiply the ordinates of Figure 10 by 2.4/3.89, or .62.

From Figure 10 we can conclude that 50,000 g's of centrifuge acceleration are not likely to significantly stress a silicon chip attachment, even if the voids ratio is very large. For example, considering a chip thickness t of 6 mils and a voids ratio V of 90 percent, we obtain a bond stress of only

$$S_{actual} = (420)(.62) = 260 \text{ psi}$$

Since bond strengths are measured in thousands of psi for most bonding materials, the developed stress of 260 psi is not likely to cause separation of this poorly bonded chip.

The situation is slightly better in the case of a ceramic <u>substrate</u>, because of its greater thickness. For example, a substrate of 50 mils thickness with a voids ratio of 0.9 will develop a bond stress of 3500 psi, and this might be sufficient to cause separation for some bonding materials. It should be remembered, however, that this result is predicated on the assumption of 50,000 g's of centrifuge acceleration. As discussed in Section IV, such high accelerations may be unusable for the larger size packages because of their destructive flexural effect on the lid or base.

B. <u>Face-Down Bonding</u>.- If a chip is bonded face down to a few pedestals or bumps, there is effectively a high voids ratio and therefore some hope of creating significant bond stress, despite the small mass of the chip. When dealing with such chips, the pedestal area is somewhat uncertain, and it may therefore be more appropriate to study the <u>force</u> B per bump, rather than the bond <u>stress</u>, per se. Dividing the total inertia load (8) by the number of bumps, N, we obtain the following formula for B:

$$B = \frac{G\gamma abt}{N} \tag{12}$$

To study the implications of this formula, let us consider the following specific case, based on data in Reference 3:

γ = 2.4 grams/cc (silicon)

a = b = 40 mils

t = 6 mils

N = 10 bumps

Then the chip volume is

$$abt = (.040)(.040)(.006)\text{in.}^3 = 96 \times 10^{-7}\ \text{in.}^3 = 157 \times 10^{-6}\ \text{cm}^3$$

and for a 40,000-g centrifuge acceleration, Eq. (12) will give

$$B = \frac{(40{,}000)(2.4)(157 \times 10^{-6})}{10} = 1.5\ \text{grams} \tag{13}$$

as the force per bump. Approximating the contact surfaces as circles and estimating their diameters to be between .0010 in. and .0018 in., we can compute from the above result the following possible range of stress in the bond:

$$S_{actual} = 4210 \text{ psi to } 1300 \text{ psi} \tag{14}$$

For such a chip, Method 2011.1 of MIL-STD-883A (Reference 1) specifies a required strength of 5 grams per bump in a "destructive shear test." Thus, the 1.5-gram force obtained in Eq. (13) can be considered to be at the threshold of significance, but not severe enough to be equivalent to the MIL-STD-883A requirement. The stress values of Eq. (14) are also at the threshold of significance. One can scale up the results in Eqs. (13) and (14) by increasing G, but the remarks at the end of the previous section regarding the danger of high G's are equally pertinent here.

IV. LIDS AND BASES OF RECTANGULAR FLAT-PACKS

As discussed in Reference 4, an acceleration of G g's normal to the lid or base of a package is equivalent to a uniform lateral pressure p of the following magnitude:

$$p = G\gamma t \tag{15}$$

where t is the thickness of the lid or base and γ is the specific weight of its material*.

The equivalent pressures given by Eq. (15) can indeed be significant, as the following example will show: Take $G = 15{,}000$, $\gamma = .140$ lb/in.^{3} (ceramic), and $t = .025$ in. Then the equivalent pressure is

$$p = (15{,}000)(.140)(.025) = 52.5 \text{ psi} \tag{16}$$

This is in the range of pressures specified for hermeticity testing in Method 1014.1 of Reference 1. Such "pressures" can be expected to produce the following significant mechanical effects, as discussed in Reference 4:

(a) Flexing of the lid, leading to bending moments in lid-to-wall seal which tend to aggravate defects in that seal. This effect is most pronounced in the middle of the longer sides.

(b) Collapse of a ductile lid and cracking of a ceramic lid or base. The likelihood of these effects increases as the package size goes up.

Another effect, not discussed in Reference 4, is the following:

---

*Equation (15) assumes the lid or base to be of a single material. In the case of a two-component base (e.g., a ceramic and Kovar combination), γt should be replaced by Γ, the weight per unit <u>area</u> of the base.

(c) Flexing of the base, which induces interlaminar shear stress in the bond between the base and a substrate attached to it, or between a substrate and a chip attached to it. These shear stresses, which are analogous to the "VQ/I" shear stresses of beam theory, can be more significant than the ones induced directly by the inertia loading and which were discussed in Section III.

Thus, it appears that centrifuge acceleration can produce significant flexural effects on the lids and bases of flat-packs, thus simulating the flexure produced by lateral pressure, constant acceleration as in a cannon-launched device, squeezing of the package during normal handling, or flat-wise impact due to accidental dropping of the package onto the floor (see Reference 5).

However, although the centrifuge is capable of the above important simulations, it is not necessarily to be recommended for that purpose. The same flexural actions can be produced with less difficulty by placing the package in a closed vessel which is then pressurized or evacuated. In this way the troublesome problem of properly supporting the package in the centrifuge is avoided. At the same time, if external pressure is used, one has accomplished the first step of a gross leak test for hermeticity. (The follow-up step would consist of inserting the package into a warmed fluid bath and watching for bubbles.) One sacrifices only the capability of exerting more than 14.7 psi of outward effective pressure on a lid or base, a capability which the centrifuge has in principle if the complicated support problem can be overcome.

V. CONCLUSIONS

In this report we have assessed the capabilities of the centrifuge as a stressing device for the following microelectronic components: wires and wire bonds, chip and substrate attachments, lids and bases of rectangular flat-packs. The conclusions to be drawn from this study are as follows: (1) The centrifuge is of marginal (or less) utility for the stressing of wires and wire bonds, because of the low mass of these components and possible strength limitations of the package. (2) For the same reasons, the centrifuge is of marginal (or less) utility for stressing normal chip-to-substrate attachments. (3) However, the centrifuge might be capable of producing significant bond stresses in chips which are bonded to a few pedestals or bumps, as in face-down bonding. (4) The centrifuge might also be capable of producing significant stresses in substrate-to-package bonds. (5) The centrifuge can produce significant flexural stresses in lids and bases of the larger flat-packs, but these effects can be more easily produced by hydrostatic pressure.

The following is a listing of the main quantitative results of the present study:

(a) Figures 4 and 7, which embody the results of the stress analyses of a wire in a centrifuge or pull test, taking the extensibility of the wire into account. (The wire extensibility effect, which has been ignored in prior analyses, is usually not important, but it can become important if the wire has very little or no initial slack.)

(b) Figure 8, which enables one to determine pull tests and centrifuge tests that are equivalent insofar as their stressing of wires and wire bonds is concerned.

(c) Equation (7), which epitomizes the above equivalence information into a simple formula that is valid for wires of normal loop height.

(d) Figure 10, which enables one to estimate centrifuge-induced bond stresses in chip-to-substrate and substrate-to-package bonds as a function of the fraction V of voids in the bonding area.

(e) Equation 12, which enables one to estimate the centrifuge-induced force per pedestal for chips which are bonded face down to a few pedestals or bumps.

(f) Equation 15, which enables one to determine hydrostatic pressures and centrifuge accelerations that are equivalent insofar as their flexing of the lids and bases of flat-packs is concerned.

APPENDIX A

STRESS ANALYSIS OF A WIRE IN A CENTRIFUGE TEST

1. Derivations.- We consider a perfectly flexible wire with bonds at the same level, as shown in Figure 11(a), and having an unstressed length of L_o. Under an inertia loading parallel to the y-axis it elongates an amount e, developing a stressed length of $L = L_o + e$. The total inertia load is the known quantity

$$Q = G\gamma AL_o \tag{A1}$$

where γ is the specific weight, A the cross-sectional area of the unstressed material, and G the number of g's of acceleration. The total load Q will be assumed uniformly distributed along the stressed length L, giving rise to a constant load per unit length of the following magnitude:*

$$q = Q/L = G\gamma AL_o/L \tag{A2}$$

With any point "a" of the wire we can associate the following quantities (see Figure 11(a)): Its distance s from the origin, measured along the stressed wire; its Cartesian coordinates x and y, both to be regarded as functions of s; the sloping angle $\theta(s)$; and the cross-sectional tension $T(s)$ tangential to the wire.

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*We shall be dealing only with small strains. Therefore any non-uniformity of mass distribution, due to non-uniformity of strain along the length of the wire, can be neglected. This is especially true for wires with small loop height, for in such wires the tension (therefore the strain) is nearly constant along the length of the wire.

The tension T can be broken into a horizontal component F and a vertical component V. From the free-body diagram of Figure 11(b), F is seen to be independent of s, but V to vary with s in accordance with the relationship $dV = -q ds$. This integrates to

$$V(s) = V_o - qs \tag{A3}$$

where, from symmetry and overall equilibrium,

$$V_o = V(0) = -V(L) = \frac{Q}{2} = \frac{qL}{2} \tag{A4}$$

From Figure 11(b) and Eq. (A3) we also have

$$T = \sqrt{V^2 + F^2} = \sqrt{(V_o - qs)^2 + F^2} \tag{A5}$$

$$\cos\theta = \frac{dx}{ds} = \frac{F}{\sqrt{V^2 + F^2}} = \frac{F}{\sqrt{(V_o - qs)^2 + F^2}} \tag{A6}$$

The maximum value of T occurs at the ends and is denoted by T_o. Thus

$$T_o = T(0) = \sqrt{V_o^2 + F^2} \tag{A7}$$

To facilitate the integration of Eq. (A6), let us introduce the new variable β, related to s as follows:

$$V = V_o - qs = F \sinh\beta \tag{A8}$$

Thus

$$\beta = \sinh^{-1}\left(\frac{V_o - qs}{F}\right) \tag{A9}$$

and

$$ds = -\frac{F}{q}\cosh\beta \, d\beta \tag{A10}$$

Denoting by β_o and β_1 the values of β at $s = 0$ and $s = L$, and making use of (A9) and (A4), we have

$$\beta_o = \sinh^{-1} (V_o/F) = \sinh^{-1} (qL/2F) \tag{A11}$$

$$\beta_1 = - \beta_o \tag{A12}$$

With this change of variable, Eq. (A6) becomes $dx = -(F/q)d\beta$. Integrating this equation from the origin to any other point, we get

$$x = -(F/q)(\beta - \beta_o) \tag{A13}$$

At $s = L$, $x = S$ and $\beta = \beta_1 = -\beta_o$; therefore Eq. (A13) gives

$$S = \frac{2F}{q} \beta_o = \frac{2F}{q} \sinh^{-1} \left(\frac{qL}{2F}\right) \tag{A14}$$

We shall now evaluate the elongation e from the elasticity of the wire. Equation (A5) gives the tension as a function of s. Then Hooke's law gives

$$\varepsilon = T/AE = \sqrt{(V_o - qs)^2 + F^2} \Big/ AE \tag{A15}$$

for the local strain, where E is the Young's modulus. Integration of the local strains gives*

$$e = \int_o^L \varepsilon ds = \frac{1}{AE} \int_o^L \sqrt{(V_o - qs)^2 + F^2} \, ds \tag{A16}$$

Making the change of variable from s to β, we convert this to

$$e = \frac{1}{AE} \int_{\beta_o}^{\beta_1} (F \cosh \beta)(- \frac{F}{q} \cosh \beta) d\beta \tag{A17}$$

---

*The integrand εds of Eq. (A15) implies that we are interpreting ε as the local elongation per unit of stressed length, instead of per unit of unstressed length (the usual convention). When the strains are small, there is no practical difference between these two interpretations.

which integrates to

$$e = \frac{F^2}{2qAE}\,[2\beta_o + \sinh(2\beta_o)] \tag{A18}$$

For computational purposes it will be convenient to introduce a mean strain parameter $\bar{\varepsilon}$, defined as follows:

$$\bar{\varepsilon} = \frac{e}{L} = \frac{L - L_o}{L} = 1 - \frac{L_o}{L} \tag{A19}$$

Then

$$\frac{L_o}{L} = 1 - \bar{\varepsilon}\,, \quad \frac{L}{L_o} = \frac{1}{1 - \bar{\varepsilon}}\,, \text{ and } \frac{L}{S} = \frac{L_o}{S}\cdot\frac{1}{1 - \bar{\varepsilon}} \qquad \text{(A20), (A21), (A22)}$$

It will also be desirable to rewrite Eqs. (A2), (A7), (A14) and (A18) in the following dimensionless forms:

$$\frac{qS}{AE} = \frac{G\gamma S}{E}\cdot\frac{L_o}{L} \tag{A23}$$

$$\frac{T_o}{AE} = \frac{F}{AE}\sqrt{1 + \left(\frac{qL}{2F}\right)^2} \tag{A24}$$

$$\frac{\sinh(qS/2F)}{(qS/2F)} = \frac{L}{S} \tag{A25}$$

$$\bar{\varepsilon} = \frac{1}{2}\frac{F}{AE}\left(\beta_o + \frac{1}{2}\sinh 2\beta_o\right) \div \frac{qL}{2F} \tag{A26}$$

and to take note of the following identities:

$$\frac{qL}{2F} = \frac{qS}{2F}\cdot\frac{L}{S} \tag{A27}$$

$$\frac{F}{AE} = \frac{1}{2}\frac{qS}{AE} \div \frac{qS}{2F} \tag{A28}$$

2. Computational Procedure.- We now have all the equations needed to compute the ordinates of Figure 4 by an iterative process. We assume that particular values have been selected for the abscissa $G\gamma S/E$ and the excess-length parameter R; also that an initial guess has been made of the mean-strain parameter $\bar{\varepsilon}$ (that initial guess may be zero, provided that R is not also zero). Then the sequence of computations is as follows:

(i) Compute L_o/S from Eq. (1).

(ii) Compute L_o/L, L/L_o, and L/S from Eqs. (A20) through (A22).

(iii) Compute qS/AE from Eq. (A23).

(iv) Compute $qS/2F$ from Eq. (A25) using Newton's iteration method.

(v) Compute $qL/2F$ and F/AE from Eqs. (A27) and (A28).

(vi) Compute β_o from Eq. (A11).

(vii) Compute $\bar{\varepsilon}$ from Eq. (A26).

The $\bar{\varepsilon}$ obtained in step (vii) will generally not agree with the one initially assumed. In that case, the $\bar{\varepsilon}$ of step (vii) should be used as a new initial guess and steps (i) through (vii) repeated. This should be done as many times as necessary until there is no significant difference between the guessed and the computed $\bar{\varepsilon}$ values. When this convergence has been achieved, the following step completes the calculation of the ordinate:

(viii) Compute T_o/AE from Eq. (A24).

APPENDIX B

STRESS ANALYSIS OF A WIRE IN A PULL TEST

The pull test is illustrated in Figure 3(b). In this test the tension T is constant at the value T_o throughout the wire, and Hooke's law gives

$$\bar{\varepsilon} = T_o/AE \qquad \text{(B1)}$$

for the uniform as well as the mean strain.

The calculations leading to Figure 7 are simplified if we regard T_o/AE and R as the independent variables and P/AE as the dependent variable. The pertinent equations, in addition to (B1) are

$$L = L_o(1 + \bar{\varepsilon}) \quad \text{(conventional strain definition)} \qquad \text{(B2)}$$

$$\sin\theta = \sqrt{1 - (S/L)^2} \quad \text{(trigonometry)} \qquad \text{(B3)}$$

$$P = 2T_o \sin\theta \quad \text{(statics)} \qquad \text{(B4)}$$

For computational purposes, we rewrite these as

$$\frac{L}{S} = \frac{L_o}{S}(1 + \bar{\varepsilon}) \qquad \text{(B5)}$$

$$\sin\theta = \sqrt{1 - \left(\frac{L}{S}\right)^{-2}} \qquad \text{(B6)}$$

$$\frac{P}{AE} = 2\frac{T_o}{AE}\sin\theta \qquad \text{(B7)}$$

Then the following sequence of steps will give the value of P/AE corresponding to any selected pair of values of T_o/AE $(= \bar{\varepsilon})$ and R:

(i) Compute L_o/S from Eq. (1).

(ii) Compute L/S from Eq. (B5).

(iii) Compute $\sin\theta$ from Eq. (B6).

(iv) Compute P/AE from Eq. (B7).

REFERENCES

1. Anon.: Test Methods and Procedures for Microelectronics. Department of Defense, MIL-STD-883A, 15 November 1974. (Avail. from Naval Publications and Forms Center, 5801 Tabor Avenue, Philadelphia, Pennsylvania 19120.)

2. Harry A. Schafft: Methods for Testing Wire-Bond Electrical Connections. U.S. Department of Commerce, National Bureau of Standards, Technical Note 786, November 1973.

3. Robert Moore: Reliability Test Program of Ultrasonic Face Down Bonding Technique. RADC-TR-67-128, June 1967, 624525.

4. Charles Libove: Rectangular Flat-Pack Lids Under External Pressure: Improved Formulas for Screening and Design. RADC-TR-76-291, Sept. 1976, A032490.

5. Charles Libove: Impact Stresses in Flat-Pack Lids and Bases. Syracuse University, Department of Mechanical and Aerospace Engineering, Report MAE-1229-T1, July 1977.

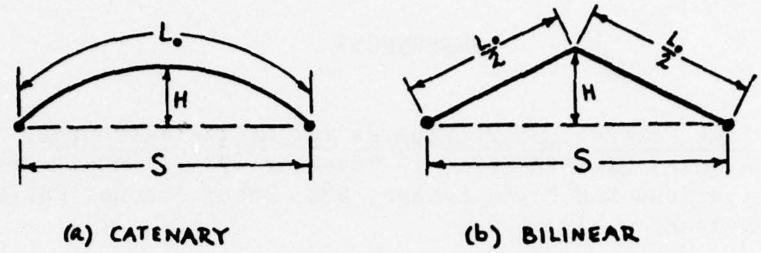

FIGURE 1. UNSTRESSED WIRE IN A CATENARY OR BILINEAR SHAPE.

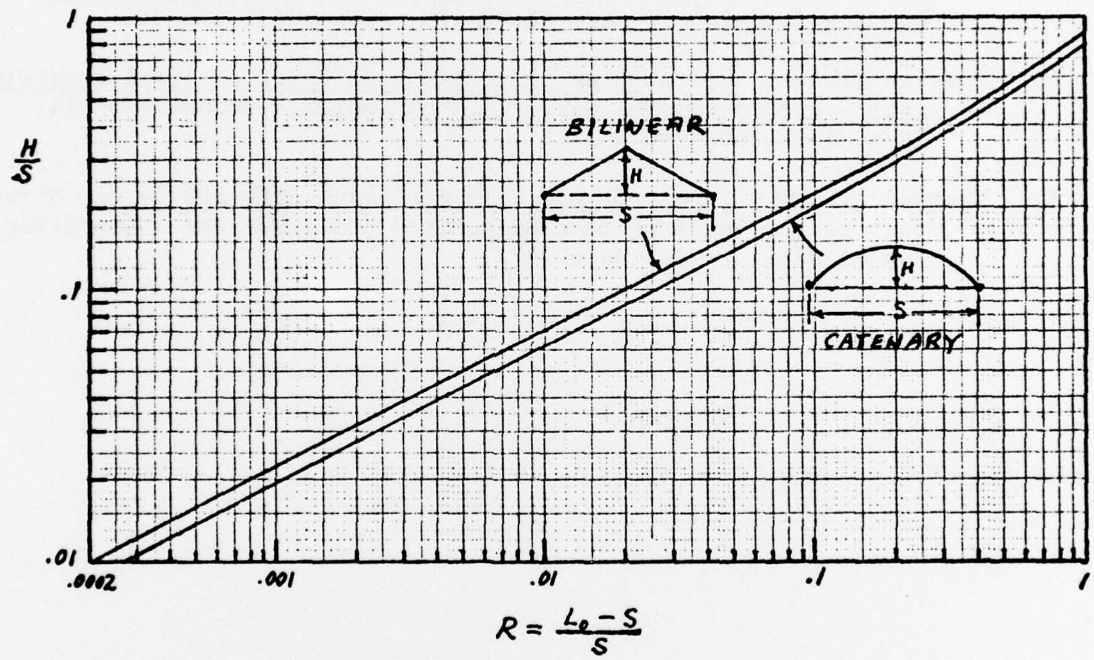

FIGURE 2. GRAPHS RELATING EXCESS-LENGTH PARAMETER R AND DIMENSIONLESS LOOP-HEIGHT PARAMETER H/S.

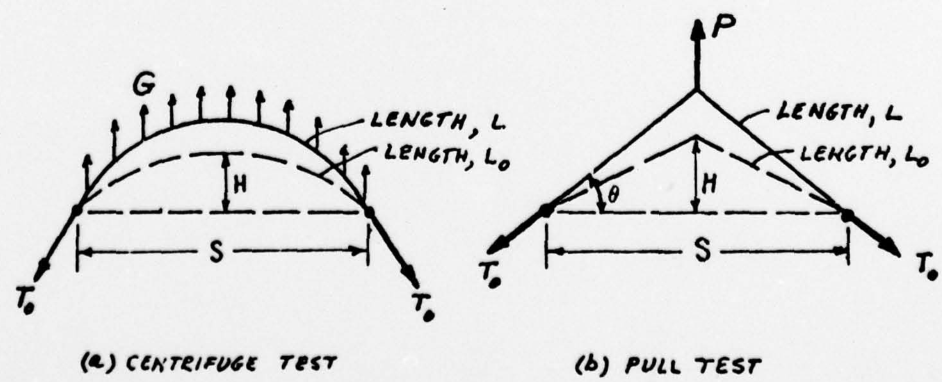

FIGURE 3. WIRE AS STRESSED IN A CENTRIFUGE OR PULL TEST. (DASHED LINES REPRESENT UNSTRESSED WIRE.)

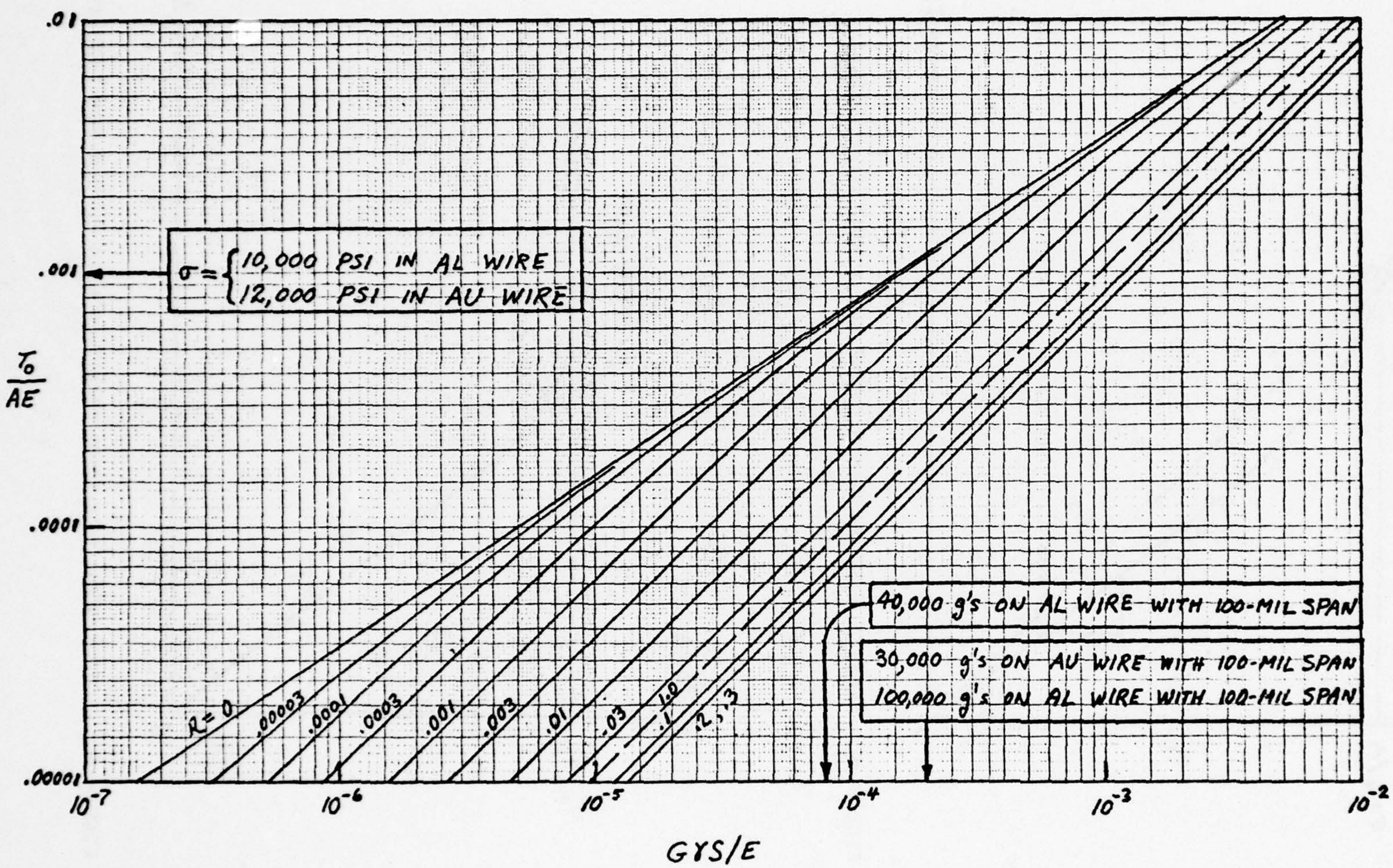

FIGURE 4. GRAPHS FOR DETERMINING BOND FORCE T_o OR MAXIMUM WIRE STRESS T_o/A IN A CENTRIFUGE TEST.

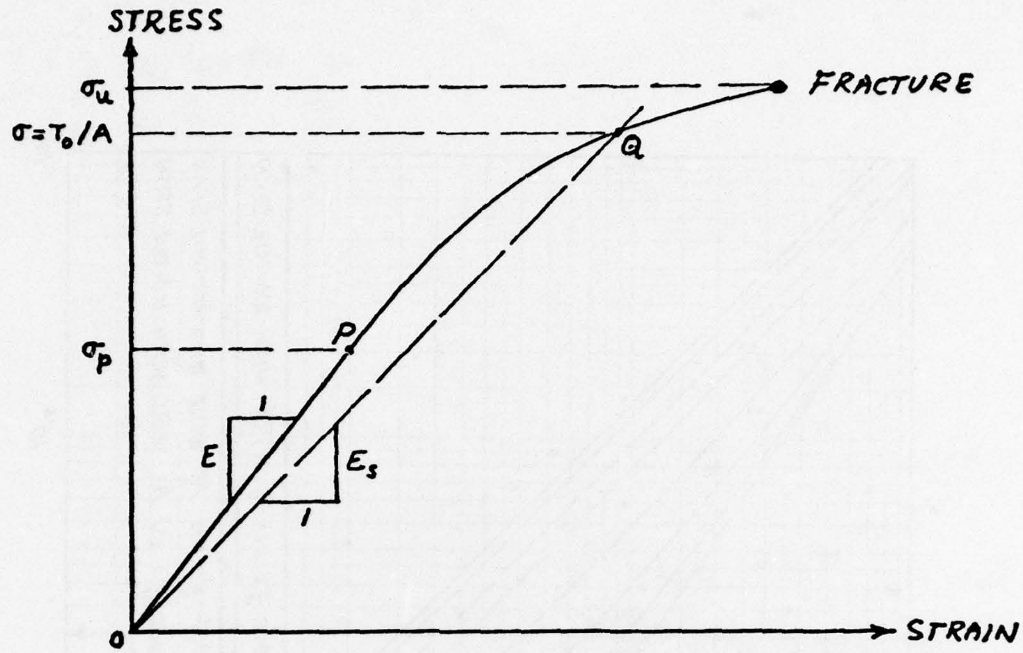

FIGURE 5. TENSILE STRESS-STRAIN CURVE FOR A DUCTILE MATERIAL.

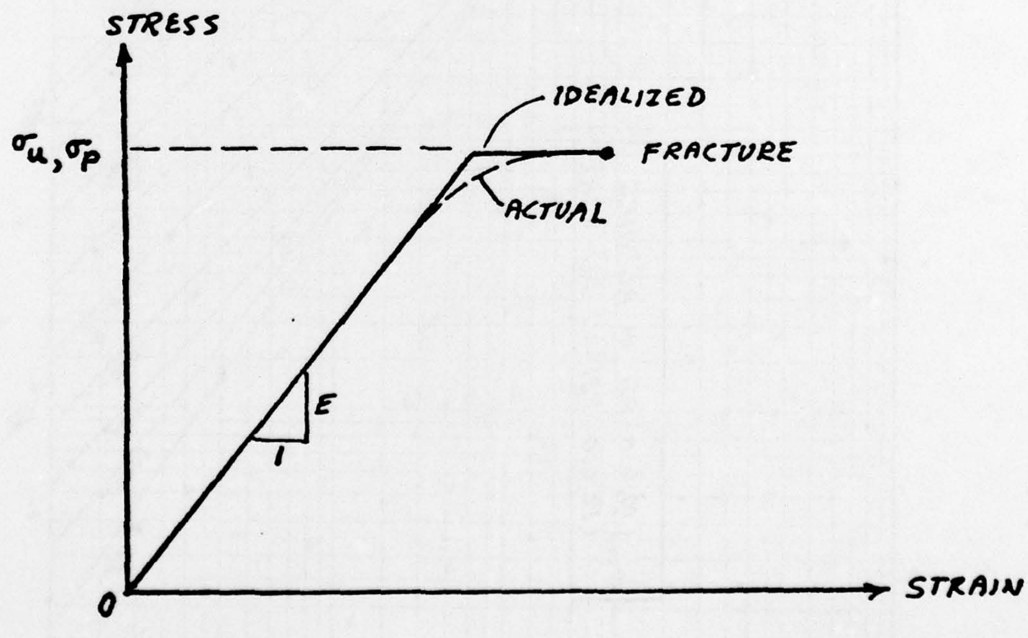

FIGURE 6. ACTUAL AND IDEALIZED STRESS-STRAIN CURVES FOR HARD-TEMPER WIRE.

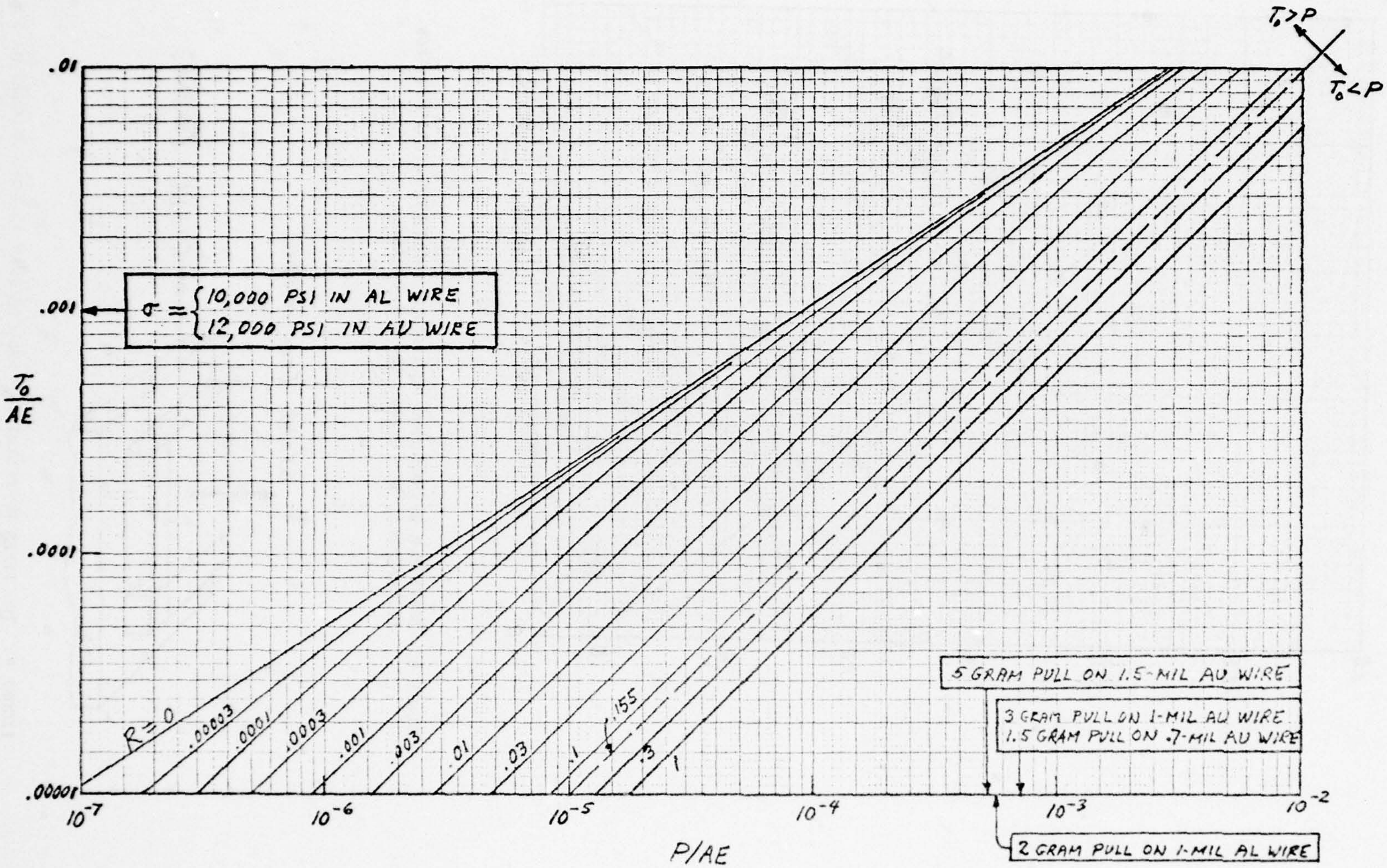

FIGURE 7. GRAPHS FOR DETERMINING BOND FORCE T_o OR WIRE STRESS T_o/A IN A PULL TEST.

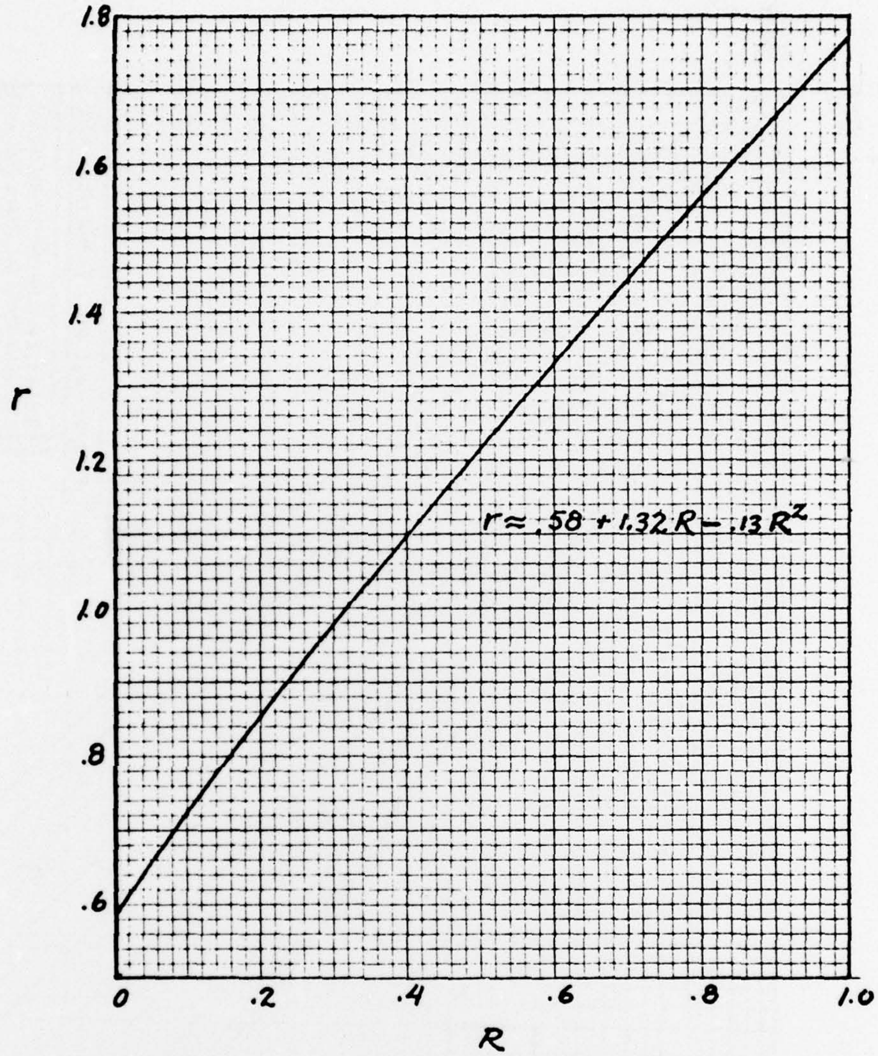

FIGURE 8. GRAPH FOR DETERMINING EQUIVALENT VALUES OF G AND P. (FOR EQUIVALENCE, $P = G\gamma SAr$ OR $G = P/\gamma SAr$.)

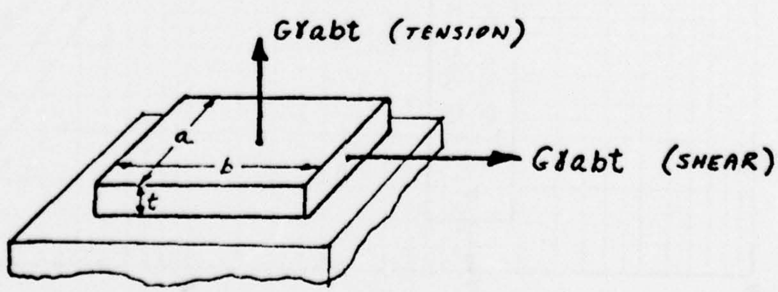

FIGURE 9. TWO TYPES OF CENTRIFUGE-INDUCED INERTIA LOAD ON CHIP OR SUBSTRATE.

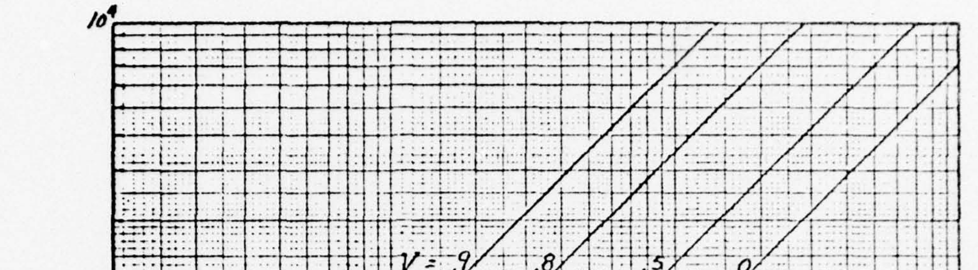

FIGURE 10. BOND STRESS FOR 3.89 GRAMS/CM^3 SUBSTRATE AT 50,000 g's. (FOR SILICON CHIP OF 2.4 GRAMS/CM^3 DENSITY, MULTIPLY ORDINATES BY .62. FOR G g's, MULTIPLY ORDINATES BY G/50,000.)

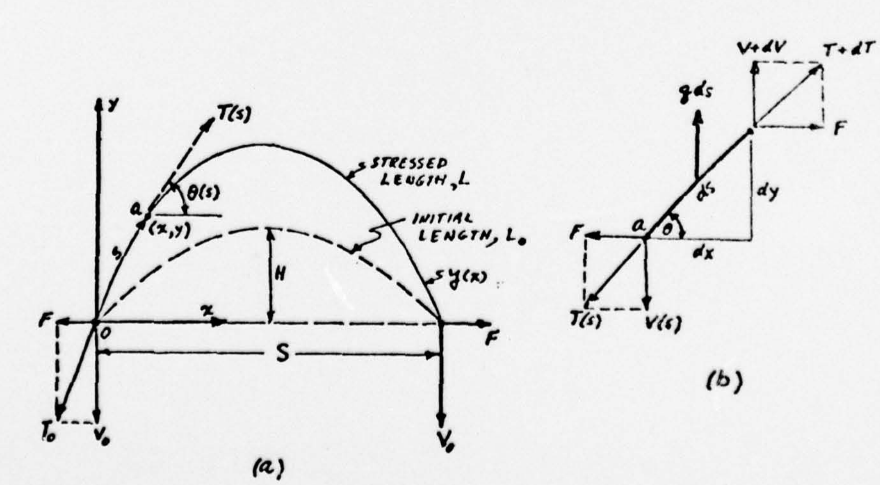

FIGURE 11. WIRE IN A CENTRIFUGE TEST. (a) ENTIRE WIRE. (b) INFINITESIMAL ELEMENT.